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A distinction between voluntary/controlled and stimulus-driven/automatic behavior has been separately applied to the effects of frontal lobe lesions, individual differences in "general intelligence" or Spearman's g, and interference between dissimilar, concurrent tasks. We suggest that these three problems are indeed closely linked, all concerning a process of selection between alternative goals or abstract requirements on behavior, especially under conditions of novelty and/or weak environmental cues to action. Among our findings are: 1. Executive deficits following frontal lesions are specifically associated with losses in fluid intelligence. 2. Conventional frontal tests have little in common besides g. 3. Across a wide range of spatial and verbal tasks, dual task interference is closely related to both g correlations and frontal lobe involvement. This may only be true, however, when the secondary task is random sequence generation, designed to avoid stereotypy. 4. Frontal patients and people from the lower part of the g distribution share a tendency to "goal neglect", or disregard of a task requirement even though that requirement has been understood. Neglect is confined to novel behavior, eliminated by verbal prompts, and sensitive to the number of concurrent goals. 5. In speeded stimulus classification, switching classification rules produces high g correlations. Correlations rapidly decrease, however, with practice on a fixed rule. The results begin to clarify the role of "executive" control in the organization of behavior.

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In the working memory model of Baddeley and Hitch (1974), the "central executive" was conceived as a supervisory system responsible for the overall control of cognition. In this report we present evidence for this idea of a general control function, and consider its role in the organization of behavior.

Phenomena

Our research has been based on three general phenomena:

1. Following damage to the frontal lobes of the brain, there can be a widespread disorganization of behavior, reflected in many different settings and in many forms of error (Luria, 1966). Examples of such disorganization include perseveration of inappropriate activity, distraction by irrelevant events or thoughts, inertia or passivity, and actions that seem impulsive, ill-judged or bizarre.

2. In the normal population, between-task correlations are almost universally positive: a person performing well on one task will tend also to perform well on others. This observation is the basis for the concept of "general intelligence", or Spearman's g (Spearman, 1927). According to Spearman's hypothesis, universal positive correlations reflect some general or g factor, making some contribution to success in all manner of diverse activities. To a large extent it is this factor that is measured in standard tests of IQ.

3. When two tasks are performed together, there is usually some interference between them. Interference is especially strong when tasks have obvious similarities - for example, when they share modality of input (Treisman & Davies, 1973) or output (McLeod, 1978) - suggesting conflicts within content-specific processing systems. Even when tasks are maximally dissimilar, however, some interference generally remains (e.g. McLeod & Posner, 1984).

Our research deals with the relationship between these phenomena, and their theoretical interpretation.

Controlled and automatic behavior

A distinction has often been drawn between behavior which is subjectively voluntary, active or controlled, and that which is stimulus-driven, passive or automatic (e.g. Bryan & Harter, 1899; James, 1890; Schneider & Shiffrin, 1977). This distinction has been applied separately to the effects of frontal lesions (e.g. Norman & Shallice, 1980), individual differences in g (e.g. Ackerman, 1988), and dual task interference (e.g. Schneider & Shiffrin, 1977).

1. A first consideration is the contrast between novel and practised or habitual behavior. Familiar or regularly-practised behavior may be relatively immune to frontal lesions (Luria & Tsvetkova, 1964); complementarily, novel behavior may be interrupted in frontal patients by familiar but inappropriate intrusions or stereotypes (Luria, 1966). Practising simple, consistent perceptual-motor tasks may reduce correlations with g (Ackerman, 1988). Novel behavior, finally, is experienced as requiring active attention, and is hard to combine with concurrent activities; habitual behavior is automatic, leaving attention free for other concerns (Bryan & Harter, 1899).

2. A second important consideration may be the strength of the environmental prompt to action, taken to distinguish "voluntary" from "stimulus-driven" behavior (e.g. Frith, Friston, Liddle, & Frackowiak, 1991). In particular, one form of prompt is a direct verbal command or suggestion. Frontal patients may need explicit verbal prompts either to continue with a task or to satisfy each of its separate requirements (Luria & Tsvetkova, 1964; Penfield & Evans, 1935). Similarly, explicit verbal directions detailing an exact manner of procedure may reduce g correlations in complex tasks (Snow, 1981).

Our research addresses both novelty and environmental prompts to action, and hence the general distinction between voluntary/controlled and stimulus-driven/automatic behavior.

Theoretical framework

"Executive" processes concern the control of action. In this section we relate novelty and prompts to some general considerations concerning action control.

1. It is commonly accepted that actions must be represented and controlled as a hierarchy of goals and subgoals (Miller, Galanter, & Pribram, 1960). An example is given in Figure 1. At any given time, behavior is an attempt to control some variable or state of the world (Figure 1, make soup). The target value for this variable is set as an abstract requirement on behavior. This variable is directly dependent on others (availability of chopped onions, hot water, etc); target values (requirements) are thus adopted for these additional variables. The process is repeated iteratively until, at the bottom of the hierarchy, we reach a level of actual motor commands. At each level of the hierarchy, the "actions" selected are in fact abstract requirements on the eventual behavior to be produced.

This process of selecting actions as progressively more detailed requirements (goals and subgoals) reflects the actual dependencies of the world. Soup depends on the availability of chopped onions, not on any details of how these onions are produced. If some disturbance arises in producing onions one way, other ways may be used to produce the equivalent result. A requirement for soup can be used to set target values for those variables it depends upon; planning is chaotic, however, if one moves straight from such an abstract requirement to a level of detailed motor commands (Sacerdoti, 1974). A requirement for soup cannot indicate directly what to do next with one's arms and legs.

2. The question arises of how, at any particular time, particular goals or requirements are chosen for the control of behavior. As shown in Figure 2, two opposite influences must be at work (e.g. Duncker, 1945; Reitman, 1965). First, new candidate goals arise through "working backwards" from active superordinate goals. For example, the goal of chopping onions arises from the super-goal of making soup. In Figure 2 these are called relevant target-states; they arise through relevance

to an already-active goal. Second, new candidate goals arise through "working forwards" from the current world state, and in particular, environmental events. For example, the goal of chopping onions may be temporarily suspended if the cat enters the kitchen with a mouse. In Figure 2 these are called possible target-states. The total set of relevant and possible target-state candidates must somehow be weighted for net importance, leading to a final selection of the goal(s) actually pursued.

3. In the context of such a competition between momentary candidate goals, practice and environmental prompts may be seen as one strong source of bias (cf. Norman & Shallice, 1980). Frequent experience of selecting a particular goal or action in some environmental and/or behavioral context may make this goal very easy to select in the current instance. So may a direct verbal command, or other strong environmental prompt. In these cases the efficiency of goal weighting procedures may be relatively unimportant; behavior seems automatic or stimulus-driven. Without such strong bias, however, reductions in the efficiency of goal weighting produce poor choices of behavior.

4. In this light we conceive of the "central executive" as a general goal weighting function. This function is impaired by frontal lesions. Individual differences in its efficiency are reflected in Spearman's g. Conflicts within it are responsible, at least in many cases, for interference between dissimilar, concurrent tasks. The function assumes particular importance when behavior is novel and environmental cues to action are weak. The following experiments test a range of predictions derived from this general set of hypotheses.

Fluid intelligence after frontal lesions

Dissociation between WAIS and Culture Fair IQs

Our hypothesis implies that "intelligence" in the sense of Spearman's g should be reduced by frontal lesions. In fact, however, frontal patients with manifest behavioral impairments may show little evidence of IQ loss (e.g. Eslinger

& Damasio, 1985; Shallice & Burgess, 1991). Indeed, it is generally held that IQ tests are inappropriate for revealing the effects of frontal lesions (Teuber, 1972). Paradoxically, it is believed that frontal patients have widespread difficulties with problem-solving, strategy choice etc, but preserved "intelligence".

To address this paradox, we considered a distinction between two different methods for estimating g. In tests like the Wechsler Adult Intelligence Scale or WAIS (Wechsler, 1955) - used in the vast majority of clinical investigations - g is estimated by averaging performance across a diverse range of sub-tests. Individual sub-tests may have rather low g correlations (Marshalek, Lohman, & Snow, 1983); furthermore, many sub-tests emphasize knowledge or crystallized intelligence, very likely reflecting g at the time of learning rather than g at the time of test (Cattell, 1971). More appropriate for estimating changes in g with brain lesions may be the alternative tests of fluid intelligence. These tests are designed both to maximize g correlations even without averaging over diverse sub-tests, and to minimize knowledge dependence. Typically they require novel problem-solving with spatial, verbal or other materials. In large-scale factor analyses it is fluid intelligence that is most closely related to g (Carroll, 1992), in the sense of a person's overall tendency to perform relatively well or relatively badly in all manner of activities.

Demonstrations of preserved or superior IQs in frontal patients have depended largely on the WAIS or similar tests. We predicted that, in patients of this sort, there would be substantial impairments in fluid intelligence.

Data for 3 patients - tested in collaboration with Paul Burgess of the University of London - are shown in Table 1. All patients had superior WAIS IQs despite manifest cognitive impairments consequent upon circumscribed frontal lesions. To assess fluid intelligence we administered Cattell's Culture Fair Test (Institute for Personality and Ability Testing, 1973), a test of spatial problem-solving with a g correlation of .81. Each patient was compared with a normal control, matched in age, sex, socioeconomic group and WAIS IQ. In the three frontal patients, there was a discrepancy of 22-38 points between WAIS and Culture Fair IQs. On the Culture Fair test, IQs of patients and controls differed by 23-60 points. These data go a good way towards resolving the paradox of preserved "intelligence" in frontal patients. Most appropriately measured, g is indeed strongly dependent on the integrity of frontal functions.

Conventional frontal tests and *g*

A good number of tests are used conventionally as markers of frontal dysfunction, including Wisconsin card sorting (Milner, 1963), verbal fluency (Benton, 1968), etc. Such conventional use has several difficulties, however. It has been reported, for example, that Wisconsin card sorting in fact does not differentiate frontal and posterior lesions (e.g. Anderson, Damasio, Jones, & Tranel, 1991). Frontal patients, furthermore, may show small or occasional deficits even on conventionally "nonfrontal" tests such as recognition memory (Warrington, 1984).

In our next study we administered a broad range of "frontal" and "nonfrontal" tests to a sample of 90 head injured patients. The study was a collaboration with Roger Johnson, Michaela Swales and Charles Freer of Addenbrooke's Hospital, Cambridge. By examining correlations between tests, we wished to establish whether conventionally "frontal" tests indeed reflect a common functional deficit, of lesser importance in "nonfrontal" tests. For this purpose we needed a broad spread of damage to both frontal and posterior systems, and in this respect the head injured group seemed ideal. Head injury produces variable, sometimes diffuse lesions, often with a major frontal component; behaviorally, "executive" deficits are common. Patients were tested from several months to several years post injury.

Four results may be described:

1. Four "frontal" tests - Wisconsin Card Sorting, a form of fluency (generating European countries), a spatial puzzle (a variant of Link's Cube; see Luria, 1966), and verbal list learning (Luria, 1966) - were used in the the main study. There were also

five "nonfrontal" tests - digit span (Wechsler, 1955), recognition memory (Warrington, 1984), object naming (McKenna & Warrington, 1983), object recognition from unusual views (Warrington & Taylor, 1973), and a pegboard test assessing motor speed (Turton & Fraser, 1986). Our first analysis concerned correlations between measures of overall performance in these nine tests.

Results were straightforward. Correlations between the four "frontal" tests were low (range .17 to .34, median .26). Indeed they were no higher than correlations between "frontal" and "nonfrontal" tests (range .12 to .55, median .29). There was no evidence here for any functional deficit common to "frontal" but not to "nonfrontal" tests. To confirm the findings, 21 patients were re-tested with further "frontal" tests - conventional verbal fluency (Benton, 1968), self-ordered memory (Petrides & Milner, 1982), the six-element test (Shallice & Burgess, 1991), tone counting (Wilkins, Shallice, & McCarthy, 1987), and perceptual reversal (Ricci & Blundo, 1990). As "nonfrontal" tests we re-administered digit span and recognition memory. Results were very much as before.

2. From several tests we could measure more specific deficits. For example, "perseverations" could be assessed in Wisconsin card sorting, country generation (repetitions), etc; "disinhibition/impulsivity" could be assessed in the spatial puzzle (rapid, unconsidered errors), country generation (bizarre intrusions), etc. Though it is often suggested that separate control functions such as switching set and inhibiting inappropriate behavior may be separately localized in the frontal lobe (e.g. Shallice & Burgess, 1991), correlations between these more specific measures tended to be even lower than correlations between total performance scores.

3. A global measure of conventional "frontal" behavior was obtained by averaging, for each patient, z-scores on each of the four "frontal" tests and two clinical ratings of "frontal" behavior (disordered conversation in interview; disorganization of daily activities). In the 21 patients given a second test battery, this global "frontal index" showed a correlation of .62 with our standard test of fluid

intelligence, the Culture Fair. An even stronger correlation of .78 was obtained between the index and a test of goal neglect, which in a later section we show to be closely related to g in the normal population.

Individually, "frontal" tests have low correlations; averaged together, they show a close relationship to g. Our hypothesis is that most tests offer a weak opportunity for executive deficits to be revealed. Some tests may be more sensitive to such deficits than others - perhaps including some conventionally "frontal" tests - but this is certainly no more than a matter of degree. Executive deficits are best captured by tests strongly correlated with g - standard tests, in other words, of fluid intelligence.

4. From MRI scans, finally, we were able to measure the extent of frontal damage in each of the 21 re-tested patients. Damage in each of 8 frontal divisions was rated on a scale from 0 to 4; for present purposes these scores were simply summed.

Figure 3 shows frontal damage as a function of general cognitive proficiency. Since our overall index of "frontal" behavior was closely related to g as measured by the Culture Fair, the average of the two (expressed as a z-score) has been used as a general proficiency score here. A negative z-score indicates cognitive proficiency below the group mean; a positive score indicates proficiency above the mean. Again the results were simple. For people whose cognitive proficiency was above average there was generally little frontal damage. People below average, however, were a mixture, some having major frontal injuries, others none. In retrospect this is exactly as we should expect, and explains why it is so hard to establish tight links between cognitive impairment and frontal lesion. A major frontal lesion moves a person into the lower part of the g distribution; many people, however, are in this same part of the distribution already, or for other reasons. Though the effect of a frontal lesion may be substantial, it is not overwhelming in comparison to the variability already present in the population.

Damage in other brain regions was also rated. In general, however, it was much less substantial, and showed no apparent relationship to cognitive proficiency.

To sum up the studies in this section: We have clear evidence of a link between frontal impairment and g. Frontal lesions produce deficits in standard tests of fluid intelligence. To a large extent, this reduction in g may account for difficulties in conventional "frontal" tests. Apart from g, indeed, these tests have little in common.

Stereotypy and dual task interference

Spatial random generation

Our hypothesis implies that dual task interference should be closely linked to both frontal lobe functions and g. In this section we describe experiments testing this prediction using a fixed secondary task, spatial random generation.

As suggested by Baddeley (1986), the generation of random sequences may be an ideal task for investigating executive functions. By definition, repetitive, familiar or stereotyped sequences - the hallmarks of automatic behavior - are inappropriate. The experience of the task is that multiple goals or requirements - avoiding stereotyped sequences (e.g. XYZ) and repetitions, distributing responses across the total available set, using both near and far transitions - continually compete for attention. In line with our hypothesis, both verbal and manual versions of the task have been shown to activate dorsolateral prefrontal cortex in man (Frith et al., 1991). In the spatial version used here, subjects rested their hands on a bank of 10 keys, one for each finger and thumb. They were asked to press keys in random order, in time with a metronome beating at a rate of 1/sec.

The most important results from a series of several studies are summarized in Figure 4. To avoid more specific sources of dual task conflict, we always paired spatial random generation with verbal tasks. In different conditions, subjects carried out either the spatial task alone, the verbal task alone, or both concurrently, in blocks of 1-2 min. Following Baddeley (1966), we find that different measures of randomness give very similar results. Figure 4 shows dual task decrements (differences between dual and single task performance) in the spatial task, using an information theoretic measure based on adjacent response pairs (i.e. frequencies of all possible transitions from one response to the next).

1. An initial experiment dealt with the effects of stereotypy. The verbal task was either counting repetitively from 1 to 10, or generating digits from the set 1 to 10 in random order. Each was done at the same rate of 1/sec, i.e. in time with the spatial random generation. Counting produced no significant decrement in spatial randomness. There was quite substantial interference, however, when both spatial and verbal random sequences were to be produced concurrently.

2. A number of experiments used passage comprehension as the verbal task. Interference with spatial random generation was modest, and independent of passage difficulty (mean results only shown in Figure 4). The results suggest that comprehension in itself makes only modest demands on executive processes.

3. Our hypothesis predicts strong interference from tasks with a major frontal lobe component. As we have said, tasks will differ in their demands on executive processes and sensitivity to frontal lesions; though this may only be a matter of degree, we chose two tasks whose frontal involvement is especially clear. One was conventional verbal fluency (in this case, generating words from semantic categories). The second was a version of Reitan's Trails B (Reitan, 1958), adapted for vocal output. At the start of each twc minute trial, subjects were given a two-digit number and a letter. In time with the metronome, they were alternately to count forward from the number and to recite the alphabet beginning from the presented letter, "wrapping around" again to A each time they reached Z. Thus a typical segment of the response stream might be H - 23 - I - 24 -J - 25.

In line with our hypothesis, both tasks produced substantial interference with spatial random generation. With only one exception (see below), these were the strongest effects obtained in any experiment.

4. Our clearest prediction is that dual task interference sho'ild be related to g correlations. As the most extreme test of this hypothesis, we had subjects carry out spatial random generation while completing a standard test of verbal IQ. The test we chose was a combination of items from the AH2 and AH3 (Heim, Watts & Simmonds, 1974), which like the Culture Fair are based on novel problem-solving. As we expected, interference in this case was maximal.

5. A final question concerned the common memory component of random generation, verbal fluency, trails, and AH2/3. We were concerned that simple memory demand might determine the pattern of interference with the spatial task. In the final experiment, subjects were given continuously-changing memory loads of 2, 4, 6 or 8 digits. Digit lists were read out by the experimenter in time with the metronome; on completion of each list the subject repeated it back, also in time, and when he or she was finished, a new list was immediately begun. List length varied between blocks. Interference with the spatial task was only substantial with list lengths of 6 or 8 items, at which point memory errors were frequent. The results contrast markedly with trails, for which the memory load at any one time is at most one number and one letter. Such results do not support a simple memory load interpetation.

6. In most experiments, interference under dual task conditions was focussed on the spatial task. The only verbal task to suffer strong interference was trails.

To sum up this series of studies: Spatial random generation shows interference from a wide range of concurrent verbal tasks. Interference is least when the verbal task is stereotyped; it is greatest for tasks with a major frontal component and/or a strong correlation with g.

<u>Profiles of dual task decrement and g correlation</u>

Our hypothesis relating dual task interference to g may be put most generally as follows. In any set of tasks or performance measures, some will be more heavily dependent on the general goal weighting function, others less dependent. More dependent tasks should show both strong dual task interference and substantial g correlations; less dependent tasks should show weaker interference and smaller correlations. Across tasks, profiles of dual task decrement and g correlation should agree.

Agreement will not be perfect for reasons of measurement. According to our hypothesis, interference with a (dissimilar) concurrent task reflects absolute demand on the goal weighting function. The correlation with g, in contrast, reflects the proportion of between-subject variance contributed by the goal weighting function; in principle, a task with substantial dependence on this function could still show a low g correlation, if for example there were other major sources of between-subject variability. In general, however, we should expect strong involvement of the goal weighting function to be associated with both large dual task decrements and high g correlations.

To compare profiles of g correlation and dual task decrement across a diverse range of measures, we chose 15 standard psychometric tests from the ETS Kit of Ekstrom, French, Harmon, & Derman (1976). Except that all were individually administered paper-and-pencil tests, the 15 varied widely in style and content, including tests of reasoning, search, fluency, memory and speed, with verbal and spatial materials. To obtain g correlations we took advantage of a U.S. Air Force study (Wothke, Bock, Curran, Fairbank, Augustin, Gillet, & Guerrero, 1991) in which 46 Kit tests were administered to very large samples of airmen. From the reported correlation matrix, we calculated each test's correlation with g defined simply as the centroid of all 46 tests. With such a large and heterogeneous battery, the centroid should provide a good g estimate (Spearman, 1927). Correlations with g for our 15 selected tests ranged from .26 to .65. These tests were then employed in two dual task studies.

1. For the first study we used a variant of random generation, designed to avoid spatial or verbal demands and to leave eyes and hands free. Subjects were instructed to tap their foot at random intervals between 1 and 5 sec. ETS test blocks ranged in duration from 2 to 7 min; subjects completed each test while simultaneously tapping random intervals.

The relationship between g correlations in the 15 ETS tests and concurrent tapping performance is shown in Figure 5. In this case redundancy (the tendency to use some intervals more than others) seemed not to be a satisfactory tapping score, showing no general dual task decrement. Instead dual task interference took the form of occasional pauses; accordingly, the tapping score we used was the proportion of intervals above the 5 sec limit. As the figure shows, g correlations and concurrent tapping performance were quite closely related, with a correlation across the 15 ETS tests of .66.

A second striking result is shown in Figure 6. All 15 ETS tests were also administered to control subjects without the tapping task, and at the end of the experiment, these subjects ranked the tests for the amount of active concentration required. Like interference on a concurrent task, this ranking may be a measure of absolute demand on the goal weighting function. As the figure shows, the two measures were indeed closely related, with a correlation across tests of .70. The impression of a requirement to concentrate is strongly predictive of interference with concurrent random interval generation.

2. Though these results are promising, we were concerned that they showed up in only one measure of performance - long inter-tap intervals - in itself not related to randomness. Accordingly we repeated the study using a new concurrent task. To obtain less ambiguous scores, we abandoned random generation. Tones at one of two alternative frequencies were presented at a rate of one every 2.5 to 3.5 sec; the subject was to respond to tones of one frequency (the target) by pressing a

footswitch. Responses were unspeeded; the measure was accuracy of target detection. This new task was paired with the same set of 15 ETS tests used before.

Results appear in Figure 7. Though dual task decrements were substantial in the tone task, this time we obtained only a weak association with g correlations. Across ETS tests, the correlation between profiles of tone task decrement and g correlation was only .33. Without further work we can draw no firm conclusion. The results of the first study may have been some artefact of the performance measure selected; alternatively, some feature of the tone task (consistency of stimulus-response mapping, length of interval between decisions, etc) may make it unsuitable for studying interference in the goal weighting system.

To sum up: When random generation is used as a secondary task, we obtain good support for our predictions. Across different concurrent tasks, interference is closely related to both frontal lobe involvement and g correlations. Results were much less promising, however, in the one experiment using a different secondary task. Before publishing these results we shall conduct further work examining possible differences between random generation and other secondary tasks.

Goal neglect

In the preceding projects we were concerned largely with establishing the link between frontal lobe functions, g correlations, and dual task decrements. In the remaining sections we deal more directly with the issues of goal or action selection, novelty, and environmental prompts.

In this section we consider the effects of verbal instructions and prompts in novel behavior. Of course, verbal commands always prompt behavior at some particular level of abstraction; in line with our previous discussion, they prompt goals or "task requirements" to be satisfied, leaving many details unspecified. Even a command to carry out some simple action, e.g. "Tie your shoelaces," is very far from a complete description of the motor activity required. Thus verbal commands are one form of environmental input to the general process of selecting goals or abstract requirements on behavior.

One characteristic of frontal patients is that single verbal commands may prove insufficient to prompt appropriate behavior. The command must be repeated, or additional prompts given (e.g. Hecaen and Albert, 1978). At the same time, the patient may show that the original command was understood and remembered; there is a mismatch between what is known of task requirements and what is actually attempted in behavior. For example, the patient may have been told that onset of a light is a cue to squeeze with the hand. When the light is seen, the patient may state, "I should squeeze," yet make no attempt to do so (Luria, 1966).

We use the term goal neglect to describe such disregard of a task requirement, even though it has been understood. We view the phenomenon as a simple model of failure of an external prompt to bring an appropriate requirement into control of behavior.

We have investigated a task in which neglect can be observed even in some members of the normal population. The stimulus sequence from a typical trial is shown in Figure 8, with time running from top to bottom. The sequence consists of a series of frames, each presented for 200 msec and separated by a further 200 msec from the next. Each frame consists of a pair of letters or digits, presented side by side in the middle of a computer screen. There are three basic task requirements:

(i) Letters should be repeated aloud as soon as they are seen. Digits are to be ignored.

(ii) The subject must watch for letters, however, on only one side at a time, left or right. The trial begins with an instruction WATCH LEFT or WATCH RIGHT, written in the center of the screen. In Figure 8, the trial begins with WATCH RIGHT, so the subject repeats E,C... while ignoring X,B...

(iii) Finally, near the end of each trial, the subject sees a further cue, which sometimes calls for a switch of sides. The cue is a + or - symbol, presented in the center of the screen. Again it lasts for 200 msec, and is separated by intervals of 200 msec from preceding and following character pairs. A + means that, for the remainder of the trial, the subject should watch the right, while a - means watch the left. In the example, the subject is to continue watching right and repeat F and Y, but if the cue had been a -, a switch to the left would have been required.

Results from studies of this task may be summarized as follows:

1. The first two task requirements are almost always satisfied correctly. The third, however, is sometimes neglected. Most commonly, the subject simply continues to report letters from the initially attended side to the end of the trial. Though this happens trial after trial (see below), explicit questions almost always reveal that the rule is actually remembered. As in cases of frontal goal neglect, the task requirement has been understood but exerts no apparent influence over behavior. When explicitly asked, neglecting subjects may report either that the + and - cues passed unnoticed, or that they were disregarded. A typical comment might be: "I realise now that the cues have been going over my head..." It is as if this aspect of task requirements somehow "slips the subject's mind".

2. Neglect is confined entirely to novel behavior, and specifically, behavior before the very first correct trial. For any given subject, one sees a series of 0...n trials on which the + or - cue is disregarded, either continuing indefinitely, or followed by immediate resolution to almost perfect performance. Once the task requirement gains control over behavior, such control is retained for the remainder of the experiment.

3. Neglect is extremely sensitive to verbal and other prompts, drawing attention to the neglected task requirement. Most effective is explicit verbal feedback from the experimenter, pointing out any errors that have been made after each trial. Such trial-by-trial feedback almost always produces resolution to good performance within a few trials. Obviously the limitation producing goal neglect

does not lie in any absolute inability to perform the task, for example because stimuli are presented too quickly.

4. In the normal population, neglect is closely related to g. Data from 3 groups of normal subjects are shown in Figure 9. Data come from an initial block of 12 trials, grouped into 3 successive sub-blocks of 4 trials each. Each sub-block is scored as "passed" if appropriate responses are made to the +/- cues, otherwise "failed", and each subject receives a score between 0 and 3 indicating the number of failed sub-blocks. In Figure 9, subjects have been sorted into bins based on Culture Fair scores, and each panel shows mean number of failed sub-blocks in the goal neglect task as a function of Culture Fair score. The left panel comes from a group of 90 young to middle-aged subjects; the middle panel comes from 41 elderly subjects, whose Culture Fair scores as expected are lower (Cattell, 1971); the right panel comes from 38 young to middle-aged subjects performing under somewhat altered task conditions (see below). The results of all 3 experiments suggest a tight relationship between goal neglect and g. Neglect is hardly ever seen among people whole Culture Fair scores are above the population mean, but is almost universal more than 1 standard deviation below the mean.

5. We have also investigated the effects of major frontal lobe lesions arising from a variety of causes, including closed head injuries, strokes, and surgically removed tumors (total N = 10). In this group, again, the first two task requirements - report of letters but not digits, and attention to the correct side at the start of the trial - are almost always satisfied. In contrast, the +/- cue is almost always disregarded without additional verbal prompting.

6. A final set of findings both generalizes neglect to a different task requirement, and provides some information on interference between concurrent tasks/requirements. To the basic letter monitoring task we added another: occasionally during the course of each trial, a brief dot would be flashed either above or below the stream of alphanumeric characters, and the subject was to respond by

pressing one of two alternative keys depending on the dot's position (above or below). Instructions for both dot and letter monitoring tasks were given before the task was actually attempted; in one group of subjects, however, the dot task was described first, while in a second group it was described last, i.e. when the subject was already bearing in mind the requirements of letter monitoring. Neglect of the +/- cue in these subjects is shown in the right panel of Figure 9; in this experiment, however, we were more interested in the possibility of neglect in the dot task. For the first group of subjects - the group for whom the dot task was described first - omissions in this task were rare, and unrelated to g. For the second group, however, we again observed a pattern of 0...n trials on which no response was made to the dots, followed by resolution within a few trials to almost perfect performance. Again neglect resolved with the introduction of trial-by-trial feedback indicating that dots had been ignored, and again, there was a strong relationship between the number of neglected trials and score on the Culture Fair test of g ($\underline{r}$ = .66, $\underline{N}$ = 18). Data as a function of Culture Fair score are shown in Figure 10. The results show that goal neglect is very sensitive to a particular form of dual task interference. A task requirement is only likely to be disregarded when several others have already been described, presumably implying a set of already-selected or active goals. It seems likely that, under these circumstances, neglect can be produced in low g subjects for task requirements of almost any description.

To sum up: These experiments reveal a difficulty that is common to frontal lobe patients and normal people from the lower part of the g distribution. This difficulty concerns neglect of a goal or task requirement, even though it has been understood and remembered. Subjectively it is as if this requirement "slips the subject's mind". Neglect is confined to novel behavior, and very sensitive to direct verbal prompting of the neglected requirement. There is also a kind of dual task interference: a task requirement is only likely to be neglected if it is specified after several others. Again the results confirm a link between frontal lobe functions, Spearman's g, and dual task interference. They suggest that this link concerns the process of activating goals or requirements on behavior, especially under conditions of novelty and weak environmental prompts.

Set switching and g

The final set of studies is more preliminary. Consistency of practice has often been considered important both in reducing dual task interference (Schneider & Shiffrin, 1977) and in decreasing g correlations (Ackerman, 1988). Stereotypy supposedly develops when stimuli are consistently associated with fixed responses or operations. In contrast, stereotypy cannot develop when there are switches of "set", such that at different times, the same stimulus requires different responses.

Switches of set have also been implicated in the effects of frontal lesions. For example, frontal patients have been suggested to show perseverations in Wisconsin card-sorting; having sorted stimuli according to one attribute (e.g. shape), they have difficulty switching to another (e.g. color) (see Milner, 1963).

We have conducted a number of experiments relating switches of set to g. Stimuli for a typical task are shown in Figure 11. The task is to find one stimulus differing from the other three along a specified dimension. There are three possible dimensions - size, indentation of top, and reflection of L - and a verbal cue preceding the display indicates the relevant dimension for this trial. The subject indicates by speeded keypress the location of the target.

Results are shown in Table 2. In an initial block of 4 minutes, the relevant dimension varied randomly from trial to trial (continual switches of set); for 7 further blocks, the relevant dimension was always size (consistent training); in a final block, switches of set were re-introduced. In this experiment, g was estimated by mean score on the Culture Fair and a verbal test, the AH4 (Heim, 1970). The table shows correlations between response time on the Ls task and g ($\underline{N} \equiv 50$) for the first switch block, the first 4 2-minute periods of consistent size training, and the final switch block.

1. The first important result is that, under switches of set, this simple classification task shows a substantial g correlation. Correlations in the range of .50 have been confirmed in three other studies using related materials (N = 90, 41 and 38 respectively).

2. The second important result concerns consistency. When the same attribute is always relevant, the g correlation starts at around the level observed with set switches, but declines to a fairly constant level after a few minutes of practice. This result has been replicated twice; in each replication the fixed-attribute condition was given <u>first</u>, showing that the initial high g correlation is not dependent on prior set switching.

These results confirm the importance of "set switching" in g. Indeed, tests of fluid intelligence like the Culture Fair and AH4 demand continual switches of procedure, rather than consistent practice with a fixed set of operations. Interestingly, the data suggest that high g correlations are not in themselves related to set-switching. Rather, set-switching prevents the rapid disappearance of high g correlations, which in themselves are characteristic of novel behavior.

3. Considered in more detail, however, the results raise as many questions as they answer. In set-switching conditions it is true that different operations must be performed on the same imperative stimulus (the 4-item array). On the other hand, practice is entirely consistent if the stimulus is taken to be the <u>combination</u> of imperative stimulus and preceding verbal cue (Duncan, 1986). Much the same could be said of the verbal trails test we described earlier as having a major frontal component. At one level it requires constant switching between number and letter series; at another level, these switches are entirely consistent, such that producing a letter is invariably a cue for changing to number, and vice versa. What <u>kind</u> of consistency leads to the rapid reduction of g correlations?

A tempting hypothesis is that g correlations remain high whenever the task requires that information be combined across stimuli that are separate in time. It has been widely suggested, for example, that frontal systems are important in carrying control signals from one stimulus to the next (Goldman-Rakic, 1987). In our "set-switching" conditions, the key consideration would be that information from the verbal cue must be carried forward to control how the subsequent array is analyzed.

We have tested this hypothesis, however, with negative results. Our method was based on the delayed match to sample task, in monkeys very sensitive to frontal lesions (Goldman-Rakic, 1987). On each trial, subjects were asked to find a previously-presented target in a 4-element array like the one shown in Figure 12. A new target was specified on each trial; this target information was to be carried forward for 3 sec for comparison with the subsequent array. Across a range of conditions, however, the g correlation was only .12 to .31 ($\underline{N} \equiv 55$).

Our results confirm that set-switching - in the sense of varying relevant stimulus dimensions - is important in maintaining g correlations across practice. More work would be needed, however, to specify what forms of consistent practice eliminate g correlations; or in other words, what conditions allow behavior to become independent of the general goal weighting function we have proposed.

Summary

Our results suggest the following conclusions:

1. Executive deficits following frontal lesions are associated with substantial reductions in g interpreted as fluid intelligence.

2. Though tests may vary in their dependence on frontal functions, conventional "frontal" tests have little in common besides g. In a head injured sample, average performance on a set of "frontal" tests correlates strongly with g. Both relate to frontal damage revealed on MRI.

3. With random generation of keypresses or time intervals as the secondary task, dual task decrements are related to both frontal lobe involvement and g

correlations. With tone discrimination as the secondary task, however, results are less clear.

4. Frontal patients and people from the lower part of the g distribution share a tendency towards goal neglect, or disregard of a task requirement even though it has been understood. Neglect provides a simple model of failure of a task requirement to assume control of behavior, in particular under conditions of novelty, weak environmental cues, and multiple concurrent goals.

5. In simple classification tasks, consistent practice rapidly diminishes g correlations. This reduction is eliminated by switches of set, in the sense of changed classification rules. The type of consistency that is effective remains to be determined.

6. We suggest that the "central executive" be seen as a general goal weighting function, selecting action requirements for the control of immediate behavior. In line with many views, this function is especially important in voluntary, active or controlled behavior, i.e. when stereotypy or automatism is avoided. This function is impaired by frontal lesions; its efficiency is reflected in Spearman's g; in many cases at least, conflicts within this function are responsible for interference between dissimilar, concurrent tasks.

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Oral presentations

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Baddeley, A.D. Working memory. The Panhellenic Conference on Psychology, Thessaloniki, May 1993.

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Baddeley, A.D. Advice on working memory and performance measurement at ONR contractors' meeting. Iowa City, October 1991.

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Table 1

WAIS and Culture Fair IQs of frontal patients (initials) and controls

	WAIS IQ	Culture Fair IQ
DS	126	88
Control	130	148
CJE	126[1]	99
Control	127[1]	148
AP	130	108
Control	128	131

[1]WAIS-R

Table 2

Speeded symbol comparison : g correlations

initial switch	size only (2 min blocks)				final switch
	1	2	3	4	
.42	.48	.30	.31	.24	.53

Figure captions

Figure 1. Standard hierarchical decomposition of an action into a goal-subgoal tree.

Figure 2. Activation of candidate goals. The current state activates possible target-states, while the goal state activates relevant target-states.

Figure 3. Estimated frontal damage (maximum damage = 32) as a function of cognitive proficiency in 21 head injured patients.

Figure 4. Spatial random generation : Decrements from single task performance produced by different concurrent tasks.

Figure 5. Relationship between g correlations and proportion of errors (intervals above range) in a concurrent interval generation task for 15 ETS tests.

Figure 6. Relationship between concentration demand and proportion of errors (intervals above range) in a concurrent interval generation task for 15 ETS tests. Concentration demand is measured on a 15 point scale (1 = minimum, 15 = maximum).

Figure 7. Relationship between g correlations and proportion of errors in concurrent tone discrimination for 15 ETS tests. Tone discrimination performed alone was almost perfect (proportion error = .04).

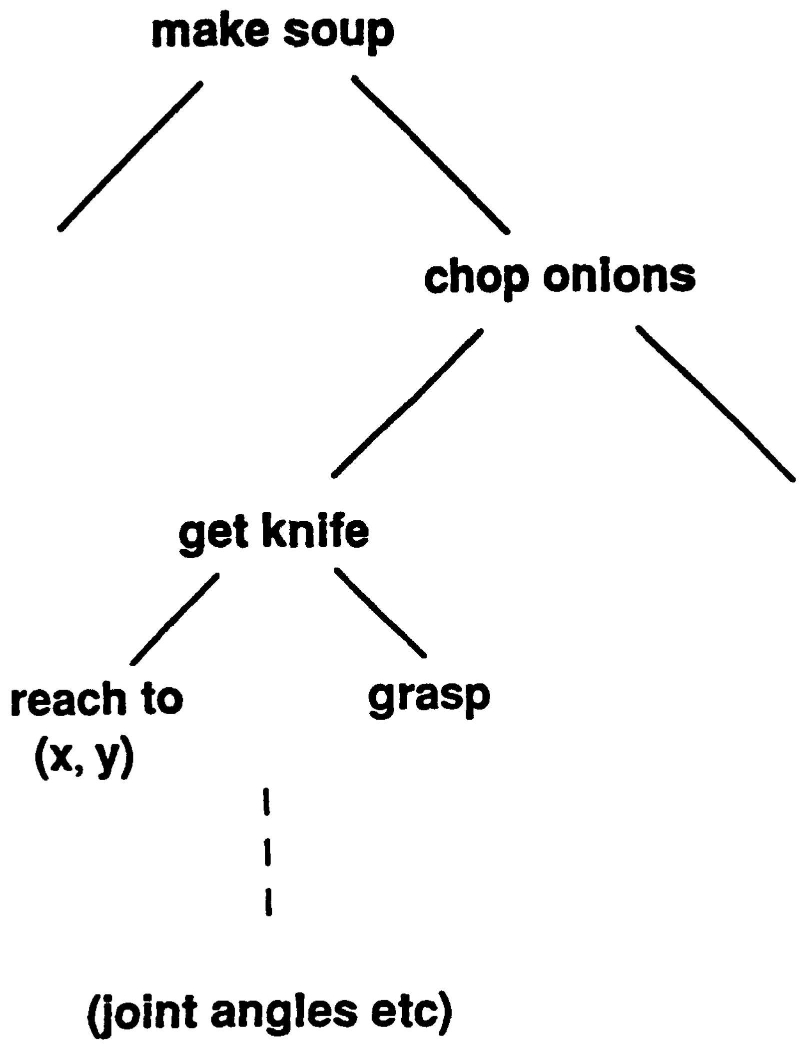
Figure 8. Sample stimulus sequence for a letter monitoring trial. Time runs from top to bottom. Each pair of characters is shown for 200 msec, and separated from the next by a 200 msec blank interval.

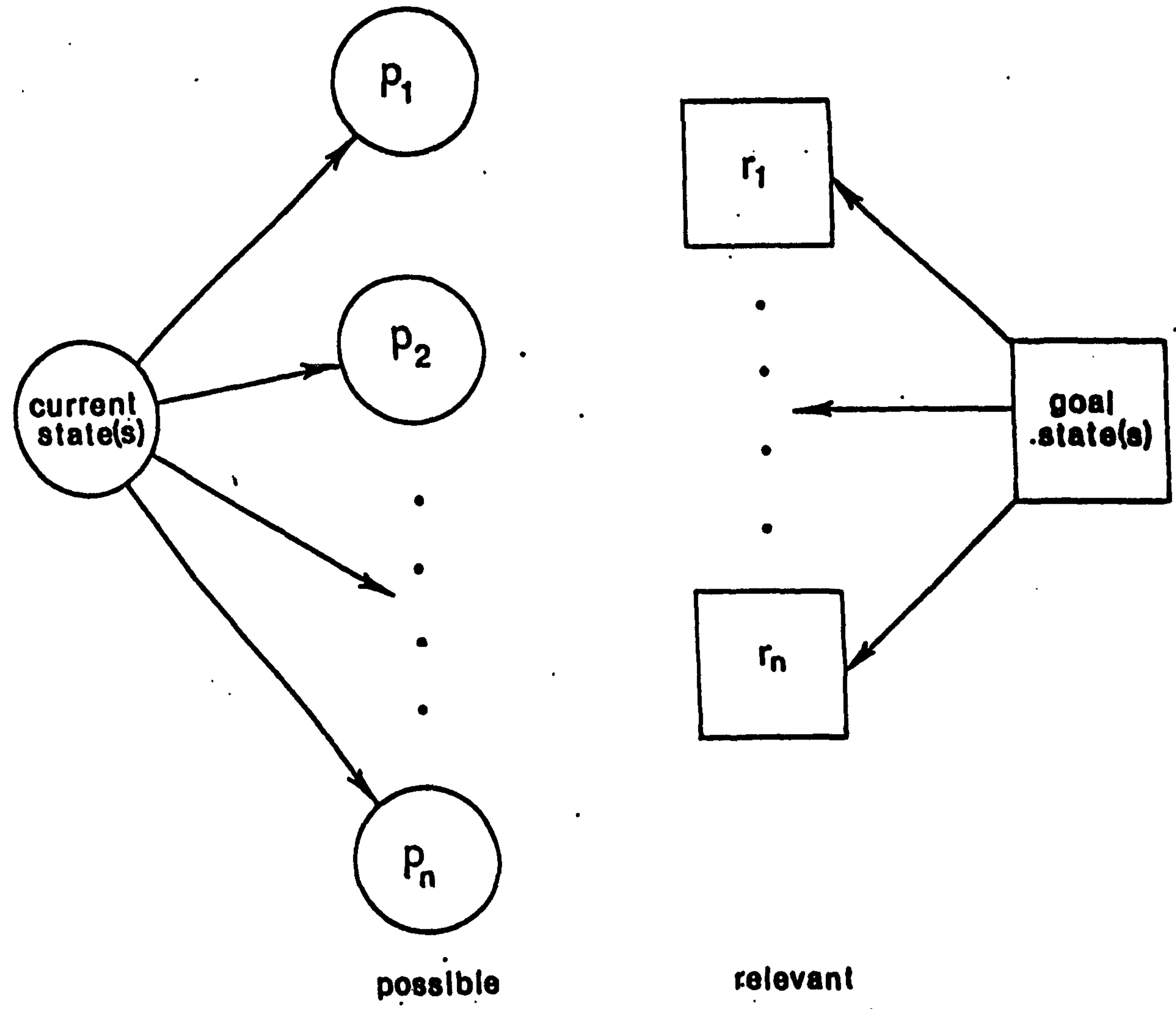
Figure 9. Relation between goal neglect (number of failed subblocks out of 3) and g in three experiments. Using the published norms, each subject's Culture Fair IQ was transformed to a z-score (mean = 0, standard deviation = 1 in the norm population), and subjects were then sorted into bins based on these z-scores. The figure shows the mean number of failed subblocks for subjects in each bin, with the number of subjects falling into the bin shown at the bottom of each column. Note that, except for the middle panel in which no subjects had Culture Fair scores above +0.5, extreme bins include all subjects beyond a z-score of +/-1.5. Left panel: 90 subjects aged 29-57. Middle panel: 41 subjects aged 60-70. Right panel: 38 subjects aged 39-49 under dual task conditions.

Figure 10. Number of dot omissions (maximum 12) as a function of Culture Fair score, separately for subjects given letter monitoring and dot instructions first. Culture Fair bins as Figure 9, except that there were no subjects with Culture Fair scores above +1.5 in the group given letter monitoring instructions first, and no subjects below -1.5 in the group given dot instructions first.

Figure 11. Example display for comparison task. Elements (Ls) vary along 3 dimensions (size, indentation of top, reflection); the relevant dimension (in this case, size) is indicated by a prior verbal cue; the task is to find the element differing from the other three on this dimension.

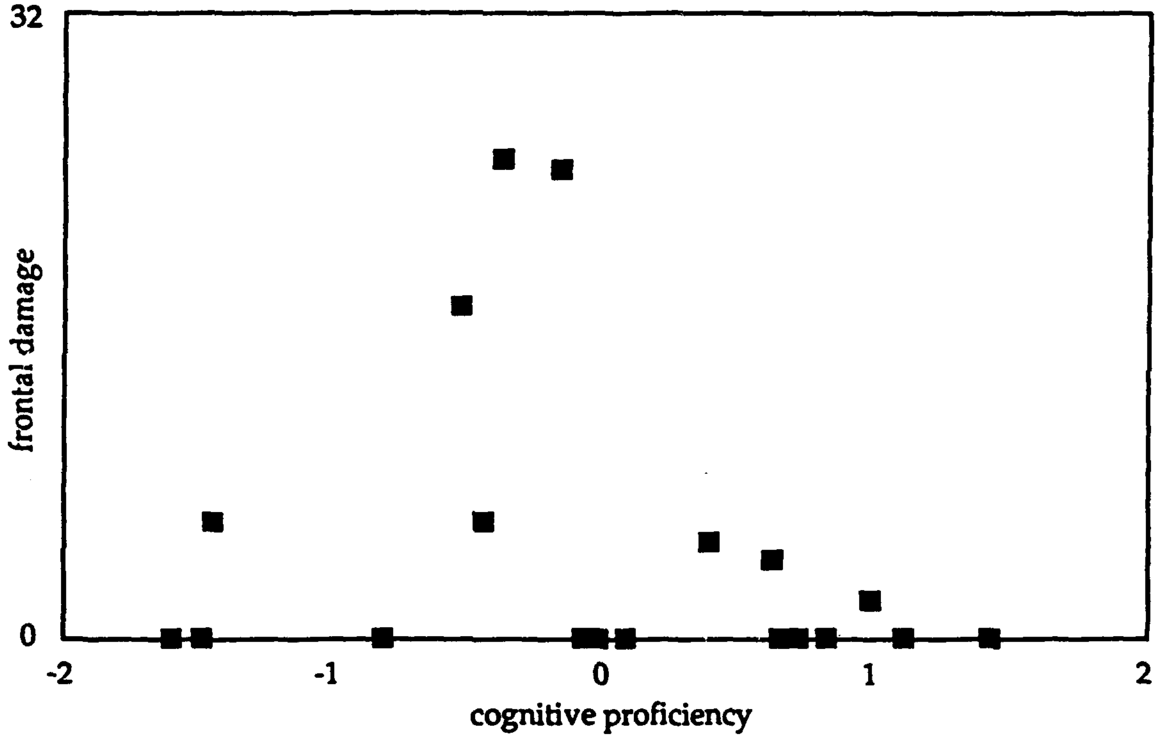
Figure 12. Example display for delayed match to sample. The task is to locate the element that is exactly identical to a previously-shown target. Relevant attributes are shape, orientation, size and texture.


make soup
chop onions
get knife
reach to
(x, y)
grasp
(joint angles etc)

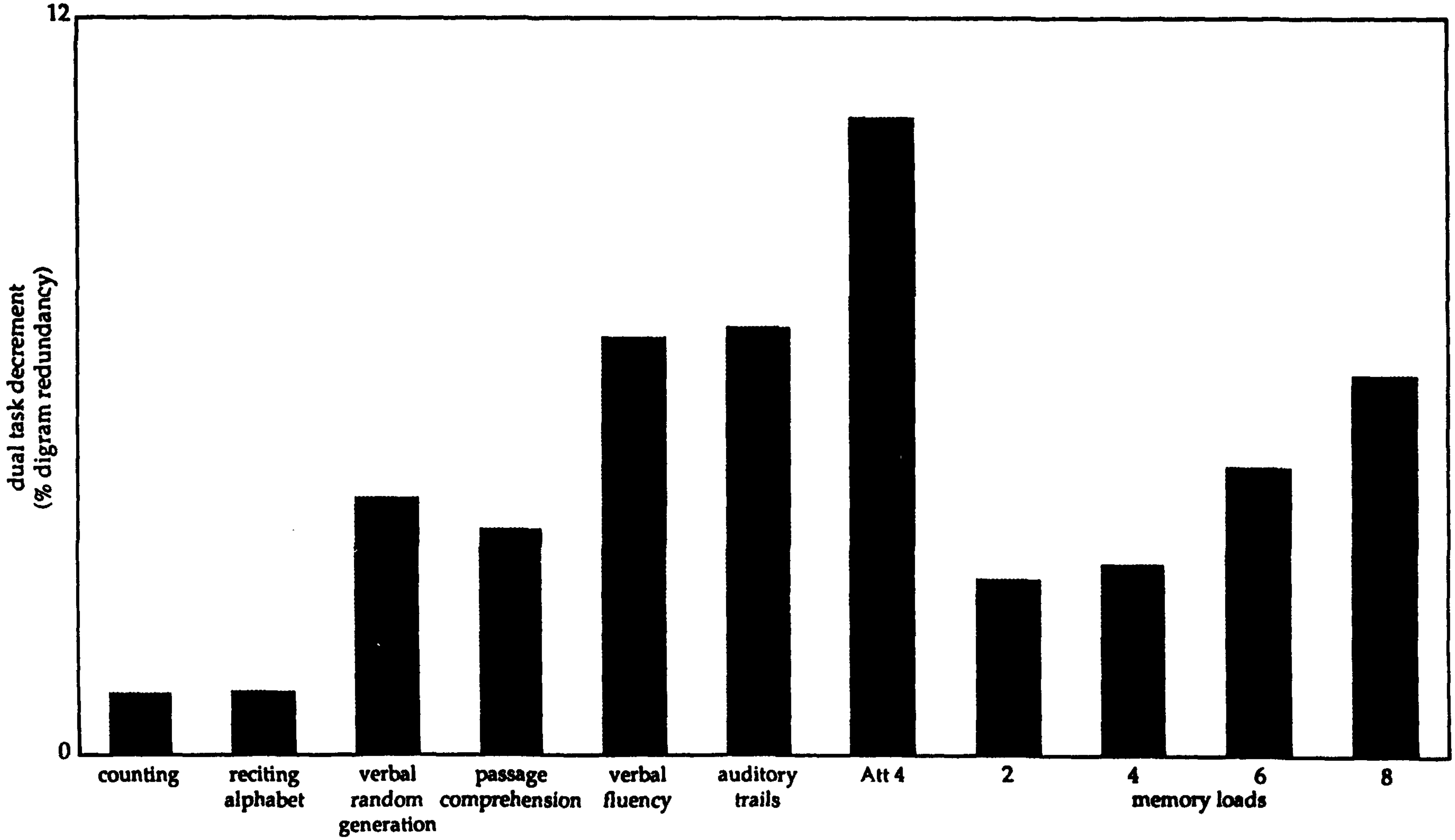


2

3

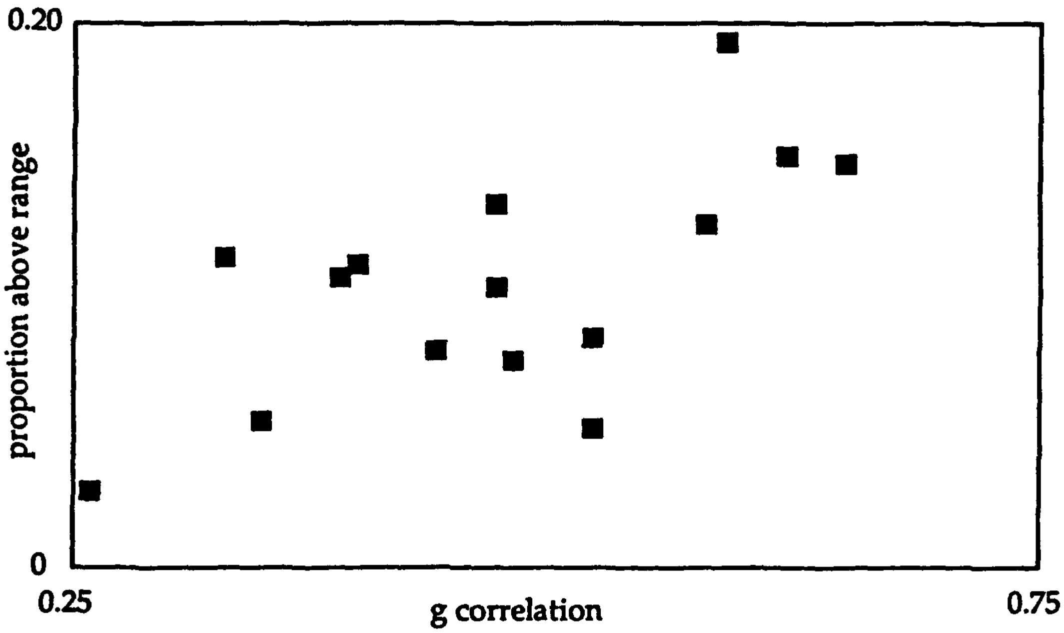


4

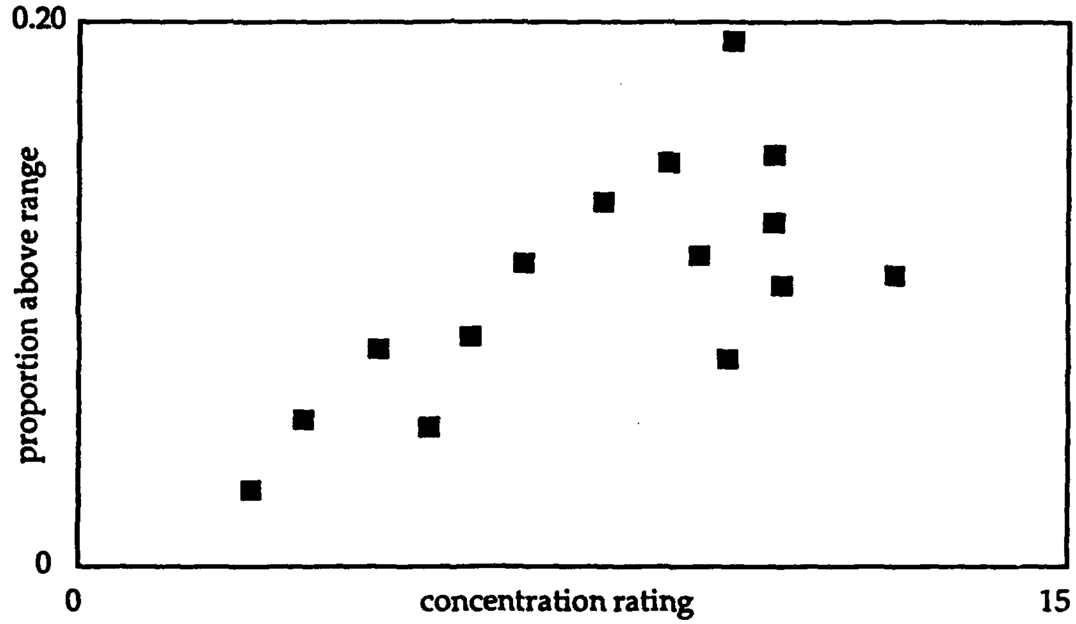


12
0
dual task decrement
(% digram redundancy)
counting
reciting alphabet
verbal random generation
passage comprehension
verbal fluency
auditory trails
Att 4
2
4
6
8
memory loads

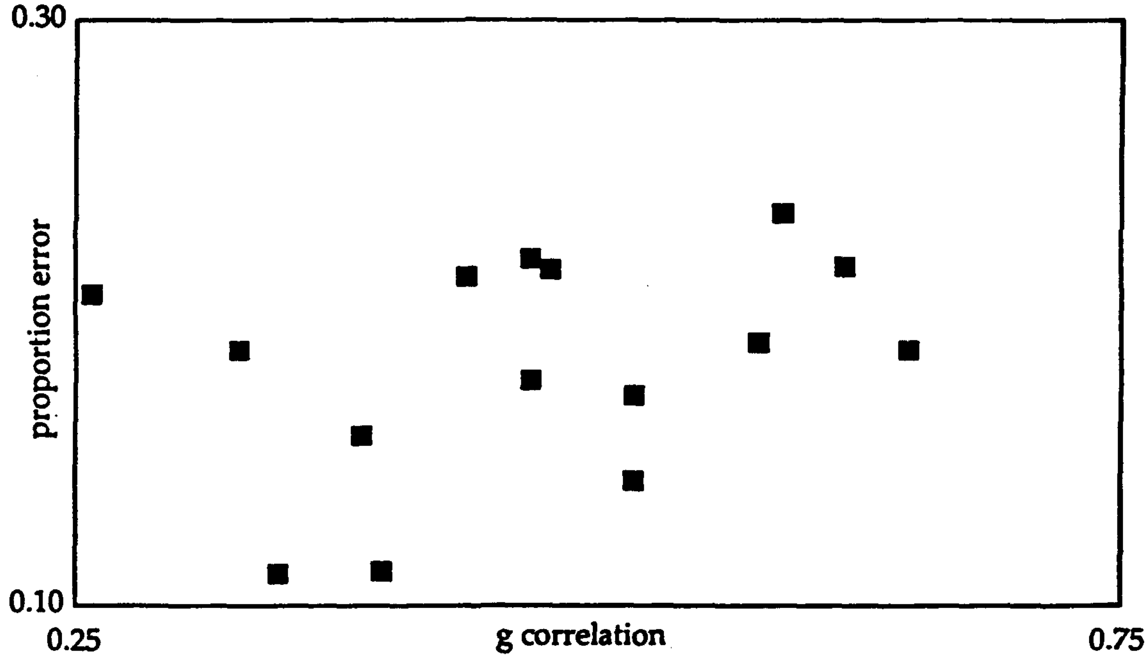
5



6



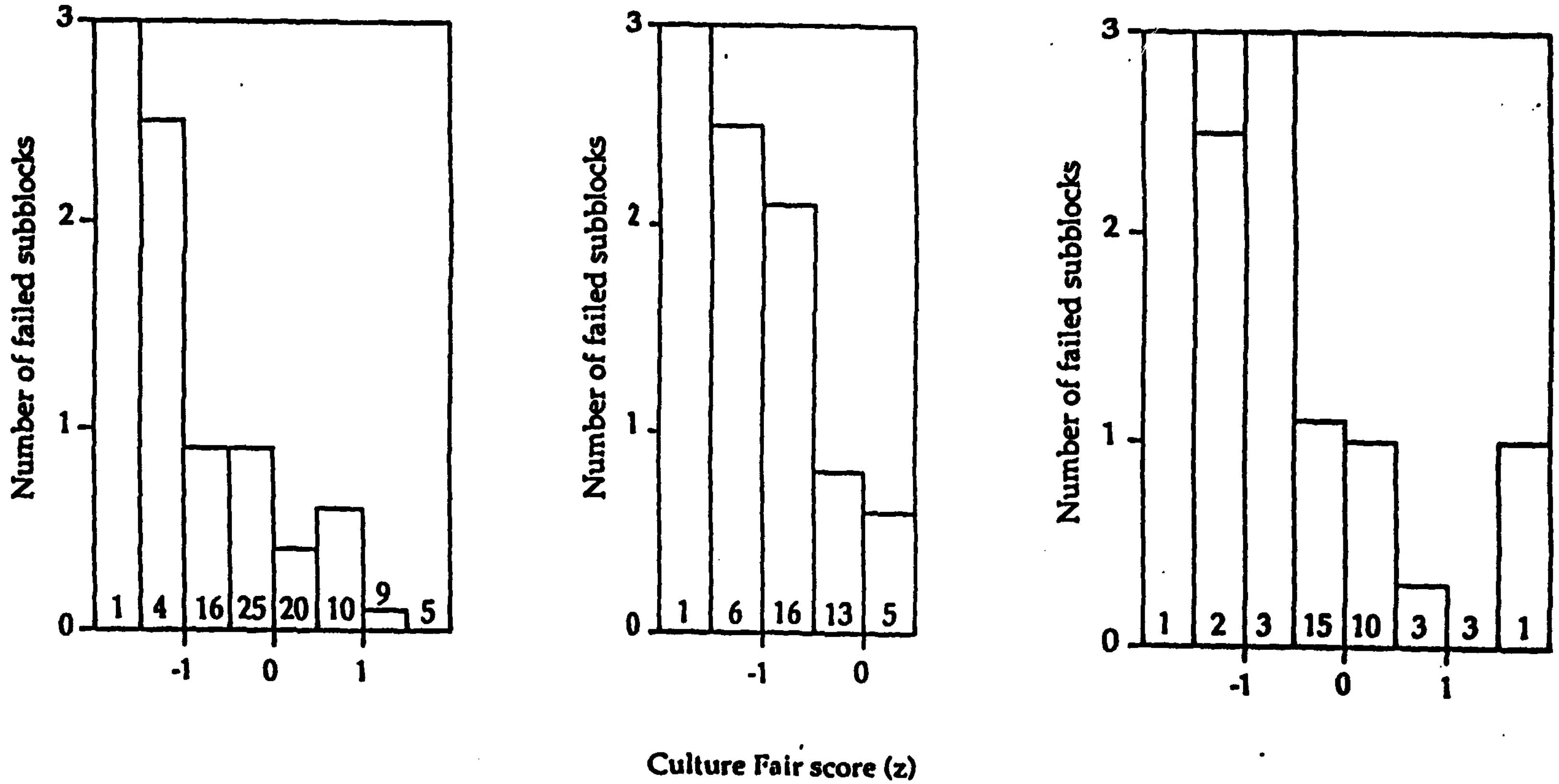
7

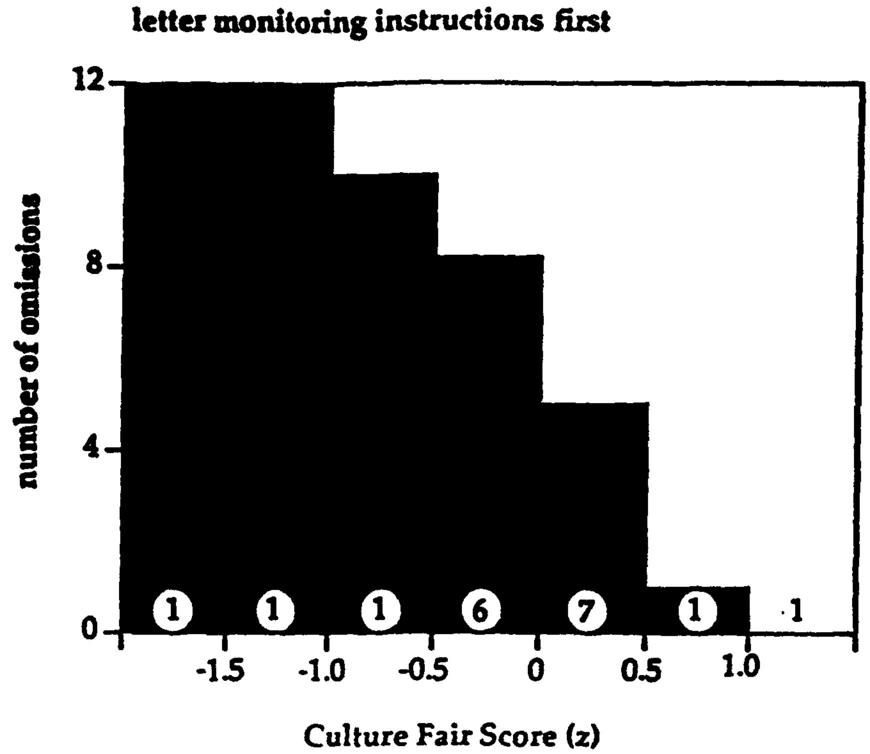


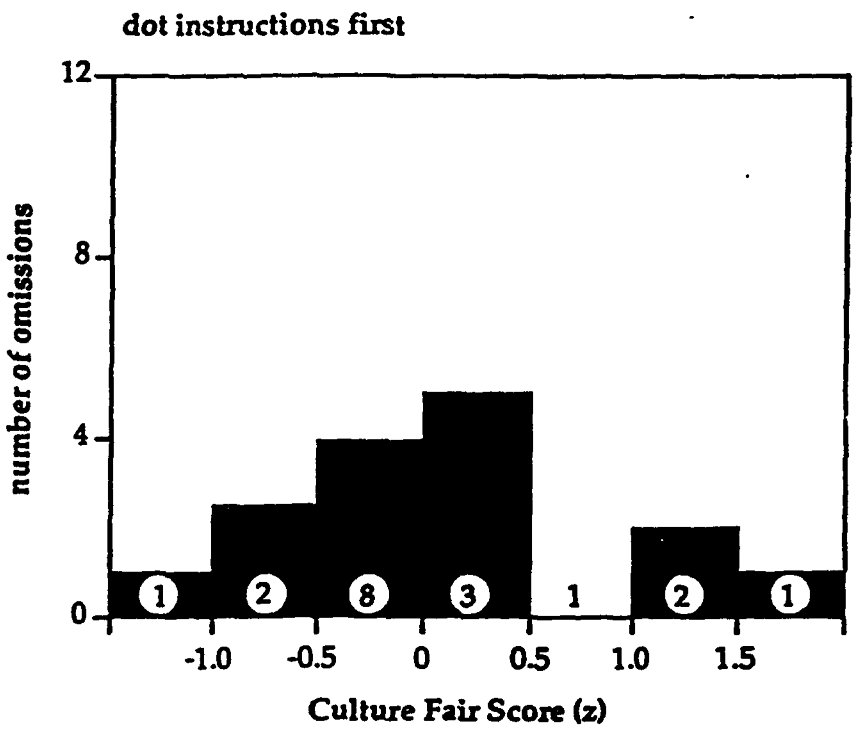
8

WATCH RIGHT

2		3
X		E
B		C
7		2
4		4
H		A
time ↓ L		Q
5		9
3		8
T		M
	+	
8		5
N		F
R		Y


Number of failed subblocks
3
2
1
0
1
4
16
25
20
10
9
5
-1
0
1
Number of failed subblocks
3
2
1
0
1
6
16
13
5
-1
0
Number of failed subblocks
3
2
1
0
1
2
3
15
10
3
3
1
-1
0
1
Culture Fair score (z)


letter monitoring instructions first
number of omissions
12
8
4
0
1
1
1
6
7
1
1
-1.5
-1.0
-0.5
0
0.5
1.0
Culture Fair Score (z)


dot instructions first
number of omissions
12
8
4
0
1
2
8
3
1
2
1
-1.0
-0.5
0
0.5
1.0
1.5
Culture Fair Score (z)

11

12